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HYBRID RAY OPTICS AND PARABOLIC EQUATION METHODS FOR RADAR PROPAGATION MODELING

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INTRODUCTION

The use of parabolic equation (PE) methods has become very popular in recent years for modeling radar propagation effects in the lower atmosphere, especially for cases in which the vertical refractive index profile changes along the propagation path. The PE method normally used is the split-step method described by Tappert (1), which has been implemented by Dockery (2), Craig and Levy (3), and others. An advantage of the PE method is its ability to compute propagation effects within the horizon as well as beyond the horizon, thereby allowing computations to be made in all regions of practical interest to radar engineers or operators with just one model. However, a significant disadvantage of the split-step PE method is that it requires extensive computation. Computational requirements increase with higher frequencies, larger antenna beamwidths, and higher altitudes for which results are desired. For many practical combinations of these parameters, the use of PE models on personal computers is impractical without extra hardware such as transputers.

This paper presents a hybrid propagation model called the Radio Physical Optics (RPO) model that uses a combination of ray optics (RO) and split-step PE methods to overcome the high computational burden of pure split-step PE methods. RPO considers four regions shown in Figure 1. At ranges less than 2500 meters and for all elevation angles above 5 degrees, RPO uses a flat earth (FE) model that ignores refractive and earth-curvature effects. For the region beyond the FE region where the grazing angles of reflected rays from the transmitter are above a small limiting value, a full RO model is used that accounts for the effects of refraction and earth curvature. The PE model is used for ranges beyond the RO region, but only for altitudes below a maximum PE altitude determined by the maximum 1024-point fast-Fourier transform (FFT) allowed. For ranges beyond the RO region and heights above the PE region, an extended-optics (XO) method is used that is initialized by the PE model at the maximum PE altitude, and uses ray-optics methods to propagate the signal to higher altitudes. Continuity of the solutions across each region's boundaries is kept to less than 0.1 dB by careful selection of the limiting RO grazing angle and the maximum PE propagation angle.

Figure 2 shows an RPO example for 3300 MHz with a transmitter at 30.5 meters above sea level. The figure shows propagation loss in dB on a gray-shade scale versus range and height. Propagation loss is the ratio of transmitted to received power using the actual transmitter antenna pattern but normalized to 0 dB antenna gain. The environment is a measured range-dependent case from Point Loma in San Diego, California on a path toward Guadalupe Isle, Mexico. The refractivity profiles along this path indicated a trapping layer that increased in height with increasing range, such that a surface-based duct existed at Point Loma and a low-elevated duct existed at 250 km. As a reference point to Figure 1, the lower left corner of the XO region in this example is at a range of 95 km and a height of 1260 m.

RAY OPTICS MODEL

Refractive index profiles are specified in RPO at one or more ranges, and are entered in terms of modified refractivity, M, defined as

$$M = (n-1+z/a)\times 10^{6} \qquad (1)$$

where n is the radio refractive index, z is height, and a is the earth's radius. Computations in the RO region do not consider range-dependent environmental effects, but rather depend only on the vertical M profile at the transmitter.

The key to RPO's efficiency is keeping the angles considered in the PE model as small as possible by maximizing the RO region. A limiting grazing angle ψ_0 for reflected rays is determined that defines the maximum range and altitude to which the RO method can be applied. ψ_0 is first computed as

$$\psi_0 = 0.04443/f^{1/3} \qquad (2)$$

where ψ_0 is in radians and f is frequency in MHz. ψ_0 from equation (2) is 2.5 times the limit given by Reed and Russell (4). The factor 2.5 was chosen to ensure that errors in the RO solution would be less than 0.1 dB. ψ_0 from equation (2) is limited to values above 0.002 radians, and then doubled if a range-dependent environment has been specified. Finally, ψ_0 is increased by an amount $\delta\psi$ to account for ducting given by

$$\delta\psi = \sqrt{2\times 10^{-6}(M_0-M_m)} \qquad (3)$$

where M_0 is M at the surface and M_m is the minimum value of M at all heights.

The RO method consists of tracing a series of direct and reflected rays through selected control points, and then interpolating the magnitudes of the direct and reflected rays and the phase angle between them at each desired RPO output point. The magnitude of each ray is computed from a spreading term relative to free-space spreading, and the phase angle is determined from the optical path length differences from the ground range for each ray. The direct and reflected ray through a given point are characterized by their elevation angles at the transmitter, α_d and α_r, respectively. The raytrace method is summarized below for a single step.

The elevation angle at the end of the step, α_1, is given by

$$\alpha_1 = \sqrt{\alpha_0^2 + 2\times10^{-6}(M_{i+1} - M_i)} \qquad (4)$$

where α_0 is the elevation angle at the beginning of the step, and M_i and M_{i+1} represent M at the beginning and end of the step. The range increment Δx, spreading increment ΔS, and optical path length difference increment ΔD over the step are given as

$$\begin{aligned} \Delta x &= (\alpha_1 - \alpha_0)/g_i \\ \Delta S &= (\alpha/\alpha_1 - \alpha/\alpha_0)/g_i \\ \Delta D &= [(10^{-6}M_i - \alpha_0^2/2)(\alpha_1 - \alpha_0) + (\alpha_1^3 - \alpha_0^3)/3]/g_i \\ g_i &= 10^{-6}(M_{i+1} - M_i)/(z_{i+1} - z_i) \end{aligned} \qquad (5)$$

where α is the elevation angle at the transmitter, and z_i and z_{i+1} are the heights at the beginning and end of the step. The total range, x, total spreading term, S, and total optical path length difference, D, are given by the sums of Δx, ΔS, and ΔD over all steps along each ray. The propagation factors, F_d and F_r, for the direct and reflected rays and the total phase angle between the rays in radians, Ω, are given by

$$\begin{aligned} F_d^2 &= f_d^2 \left| \frac{x}{(\beta_d S_d)} \right| \\ F_r^2 &= f_r^2 R^2 \left| \frac{x}{(\beta_r S_r)} \right| \\ \Omega &= (D_r - D_d)\, k + \phi \end{aligned} \qquad (6)$$

where f_d and f_r are antenna pattern factors corresponding to the elevation angles at the transmitter, α_d and α_r, respectively. β_d and β_r are elevation angles at the terminal point of each ray for the direct and reflected rays. k is the wave number $2\pi/\lambda$ where λ is wavelength in meters. R and ϕ are the magnitude and phase lag of the reflection coefficient, which are computed for horizontal, vertical, or circular polarization and include the effect of sea roughness based on wind speed in the same manner as described by Patterson et al. (5). The sum of the two ray components is given by

$$F^2 = F_d^2 + F_r^2 + 2F_dF_r \cos\Omega \qquad (7)$$

where F is the propagation factor defined as the ratio of the field strength to the free-space field strength. Propagation loss L in dB is computed as

$$L = 20 \log f + 20 \log x - 10 \log F^2 - 27.56 \qquad (8)$$

where log is base 10, f is frequency in MHz, and x is range in meters.

FLAT EARTH MODEL

The flat earth model ignores all effects from refraction and earth curvature, and computes the direct and reflected ray interference pattern using straight line paths. Full account is given to the antenna pattern and sea-surface reflection coefficient, including rough surface effects. The direct path length, r_1, and the reflected path length, r_2, are given by

$$\begin{aligned} r_1 &= \sqrt{(z - z_t)^2 + x^2} \\ r_2 &= \sqrt{(z + z_t)^2 + x^2} \end{aligned} \qquad (9)$$

where x and z are the range and height from the transmitter and z_t is the transmitter height above the surface. The grazing angle, ψ, and the direct ray elevation angle at the transmitter, α_d, are given by

$$\begin{aligned} \psi &= \tan^{-1}[(z + z_t)/x] \\ \alpha_d &= \tan^{-1}[(z - z_t)/x] \end{aligned} \qquad (10)$$

and the reflected ray elevation angle is given by $\alpha_r = -\psi$. The total phase lag, Ω, in radians is

$$\Omega = (r_2 - r_1)\, k + \phi \; . \qquad (11)$$

The propagation factor, F, for the coherent sum of the two ray components is computed by equation (7), where $F_d = f_d$ and $F_r = f_r R$. Propagation loss is computed from equation (8), substituting r_1 for x.

PARABOLIC EQUATION MODEL

The split-step PE model follows Dockery (2), where the complex field u(x,z) is advanced to u(x+δx,z) by

$$u(x+\delta x, z) = e^{i k \delta x (10^{-6} M(x,z))} \mathcal{F}^{-1}\{U(x,p)\, e^{-i p^2 \delta x / 2k}\} \qquad (12)$$

where M is the modified refractivity as defined in equation (1). The Fourier transform $\mathcal{F}$ of u(x,z) is defined as

$$U(x,p) = \mathcal{F}\{u(x,z)\} = \int_{-\infty}^{\infty} u(x,z)\, e^{-ipz} dz \qquad (13)$$

where $p = k \sin\theta$, and θ is the angle from the horizontal. In RPO, only real-valued sine FFTs are used, with which the real and imaginary parts of u are transformed separately. A filter is applied to the upper 1/4 of the field in both z- and p-spaces at each step to ensure that the field reduces to zero at the top of the transform. Transform size varies, but never exceeds 1024 points.

The starting field at x = 0 is constructed in p-space based on image theory and far-field approximations. Thus

$$U(0,p) = G\left[f_d e^{-ipz_t} + f_r R e^{i(pz_t + \phi)} \right] \qquad (14)$$

which is normalized by G such that

$$F^2 = x\, |u(x,z)|^2 \qquad (15)$$

which is used in equation (8) to compute propagation loss in dB. The magnitude R and phase lag ϕ of the reflection coefficient include polarization and rough surface effects in the same manner as used in the RO region. A Gaussian taper function, much stronger than the filter referred to above, is applied to the upper 1/4 of the starting solution. This function reduces the field up to 70 dB, in addition to any reduction by the antenna pattern.

The selection of the height increment δz between adjacent values of u and the range increment δx follows methods outlined by Tappert (1), and summarized as

$$\begin{aligned} \delta z &= \lambda N_i \\ \theta_{max} &= \frac{1}{2N_i} \\ \delta x &= 2k(\delta z)^2 \end{aligned} \qquad (16)$$

where N_i is an appropriate integer number, and θ_{max} is the maximum angle that can be accommodated in the PE solution. In RPO, N_i is determined as the maximum integer such that 3/4 of θ_{max} just exceeds the maximum elevation angle of the RO limiting ray at any height below 3/4 of the maximum PE height.

EXTENDED OPTICS MODEL

The propagation factor F is computed from the PE solution at the top of the PE region and is used to initialize an RO model in the XO region. This model traces rays, along which F from the PE solution is held constant, taking account of the full range-dependent refractivity environment, and based on initial angles β at the PE/XO boundary. If a reflected ray from the transmitter exists at the PE/XO boundary, then β is the local elevation angle of this ray at the PE/XO boundary. The greatest range at which reflected rays exist along the PE/XO boundary is called the optical limit. For ranges beyond the optical limit, β is given by

$$\beta = \sqrt{\beta_L^2 + 2\times10^{-6}(M - M_L)} \qquad (17)$$

where β_L and M_L are β and modified refractivity at the optical limit, and M is the modified refractivity at the desired range. Using linear interpolation techniques, F is defined at all points within the XO region, and propagation loss is calculated using equation (8).

COMPARISON TO OTHER METHODS

Figure 3 compares RPO results to results from a waveguide program and a split-step PE model. The case presented is a homogeneous surface based duct defined by the modified refractivity profile of Table 1. The frequency is 3000 MHz, the antenna height is 30.5 meters, the polarization is horizontal, the antenna pattern is omni-directional, and a smooth sea surface is assumed. Figure 3 plots propagation factor in dB versus altitude at a range of 185 km. Figure 3a shows the RPO results for the ducting case by a solid curve, and the corresponding standard atmosphere case by a dot-dash curve. The dotted horizontal lines in Figure 3a indicate the boundaries of the PE, XO, and RO regions for the ducting case at the 185 km range. The effects of this strong duct in all three of the RPO regions is clear from a comparison of the ducting and standard curves. Figure 3b presents waveguide results for this same case previously reported by Hitney et al. (6). The waveguide results are practically identical to the RPO results. Figure 3c presents results from a split-step PE model described by Barrios (7). These results are also virtually identical to the RPO results.

The times required to compute the ducting cases of Figure 3 on a 25 MHz IBM/PC-compatible 486 computer were 69, 381, and 310 seconds for the RPO, waveguide, and PE models, respectively. In more stressful cases, RPO has proven to be 25 to 100 times faster than split-step PE models. For some practical combinations of higher heights and frequencies and using beamwidths above a few degrees, PE models are usually impractical due to large transform size requirements. RPO has no difficulty with these applications.

One limitation of the current implementation of RPO is the use of a range-independent RO model in range-dependent environments, which in extreme cases can cause discontinuities along the RO/PE boundary. However, experience has shown that for realistic environments, such as the case of Figure 2, the limiting grazing angle is high enough to ensure acceptable RO results. A second limitation concerns rough surface effects in the PE model, which are included in the starting solution to account for higher angle effects but are ignored thereafter. Comparisons of waveguide and RPO results indicate this simplification can affect some high frequency applications in ducting environments.

CONCLUSIONS

Based on comparisons of results, RPO is as accurate as waveguide or split-step PE models. RPO can compute results for range-dependent environments in the same way PE models can, but is applicable to wider antenna patterns than typical PE models. RPO has proven to be much faster than split-step PE models, yet it requires far less memory than typical PE models. The accurate results, wider applicability, faster computation times, and smaller memory requirements make RPO an ideal model for use in all propagation assessment or engineering-aid programs, including those hosted on personal computers.

ACKNOWLEDGEMENTS

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Height m	Refractivity M units
0	367
267	401
465	354
3000	703

Table 1. Modified refractivity versus height profile for the ducting case of Figure 3.

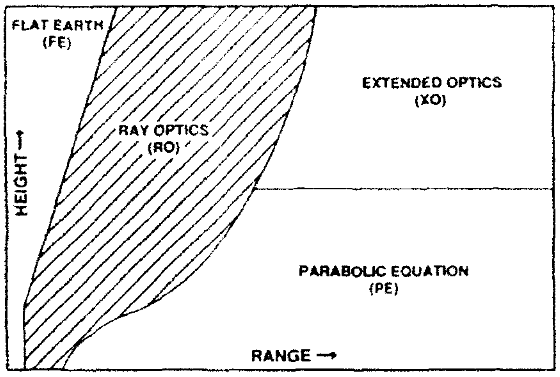

Figure 1. The four RPO regions.

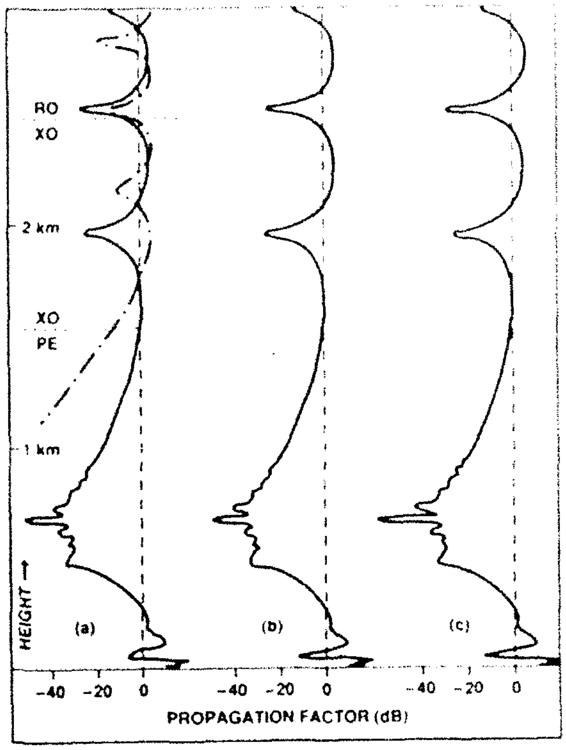

Figure 3. Propagation factor versus height for a surface-based duct from: (a) RPO, (b) waveguide, and (c) PE models. Dot-dash curve is a standard atmosphere reference from RPO.

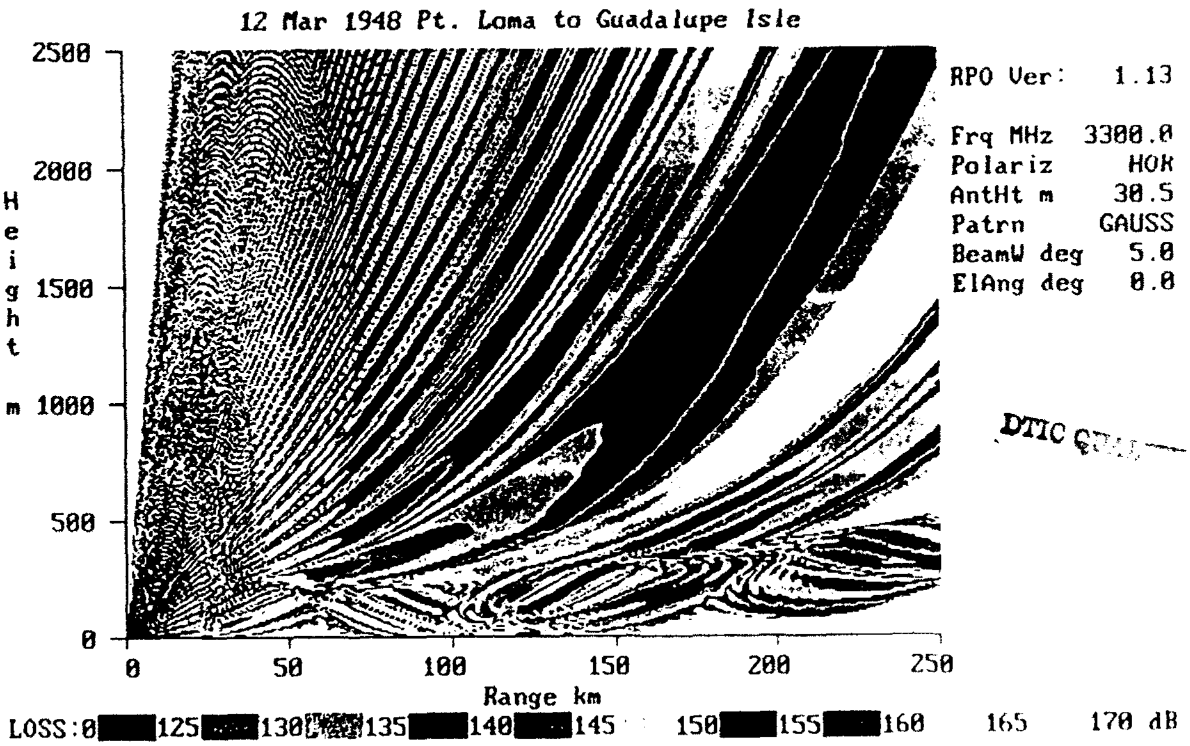

Figure 2. Sample RPO coverage display for a range-dependent environment.